SAND2012-1464P

Space Nuclear Power

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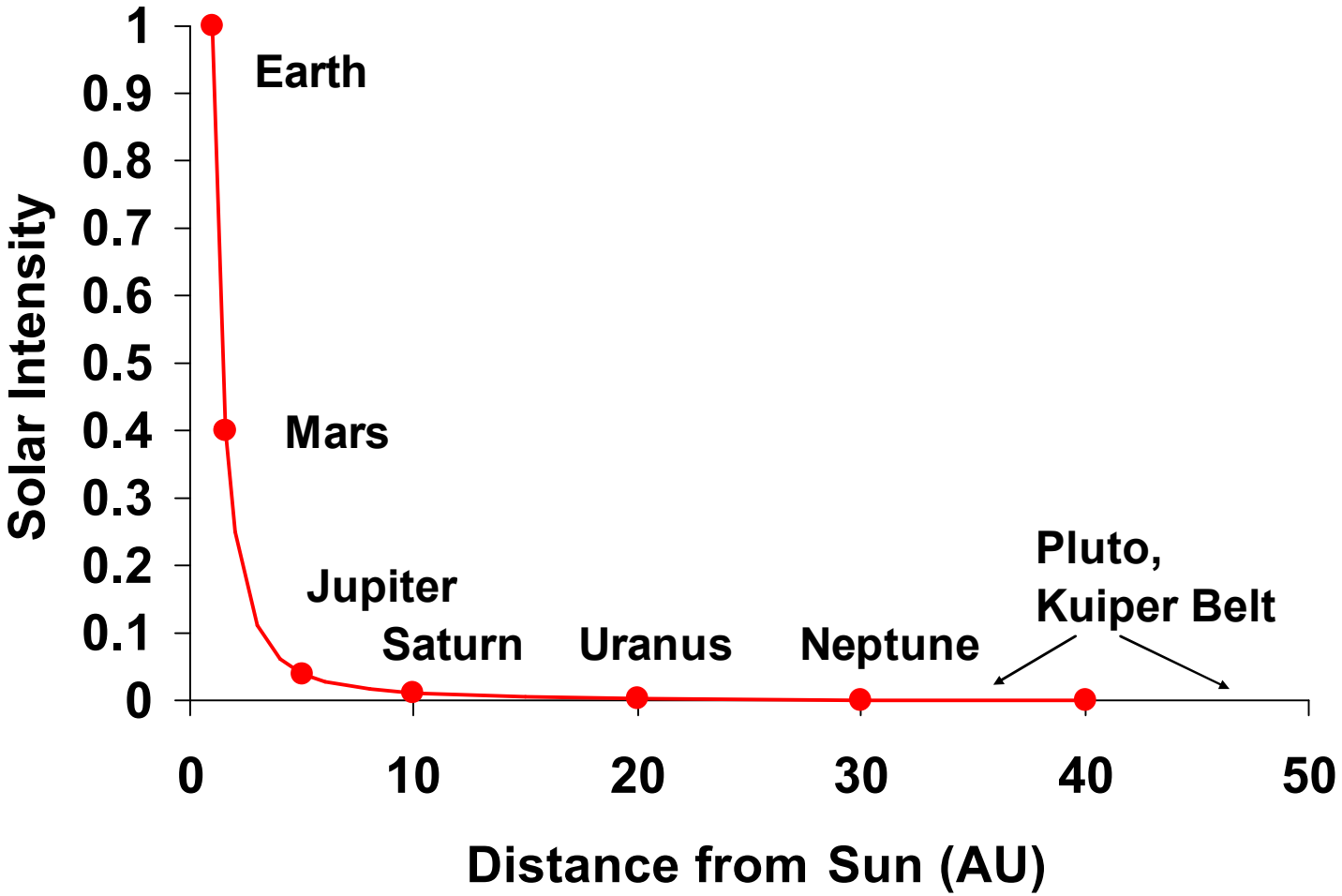
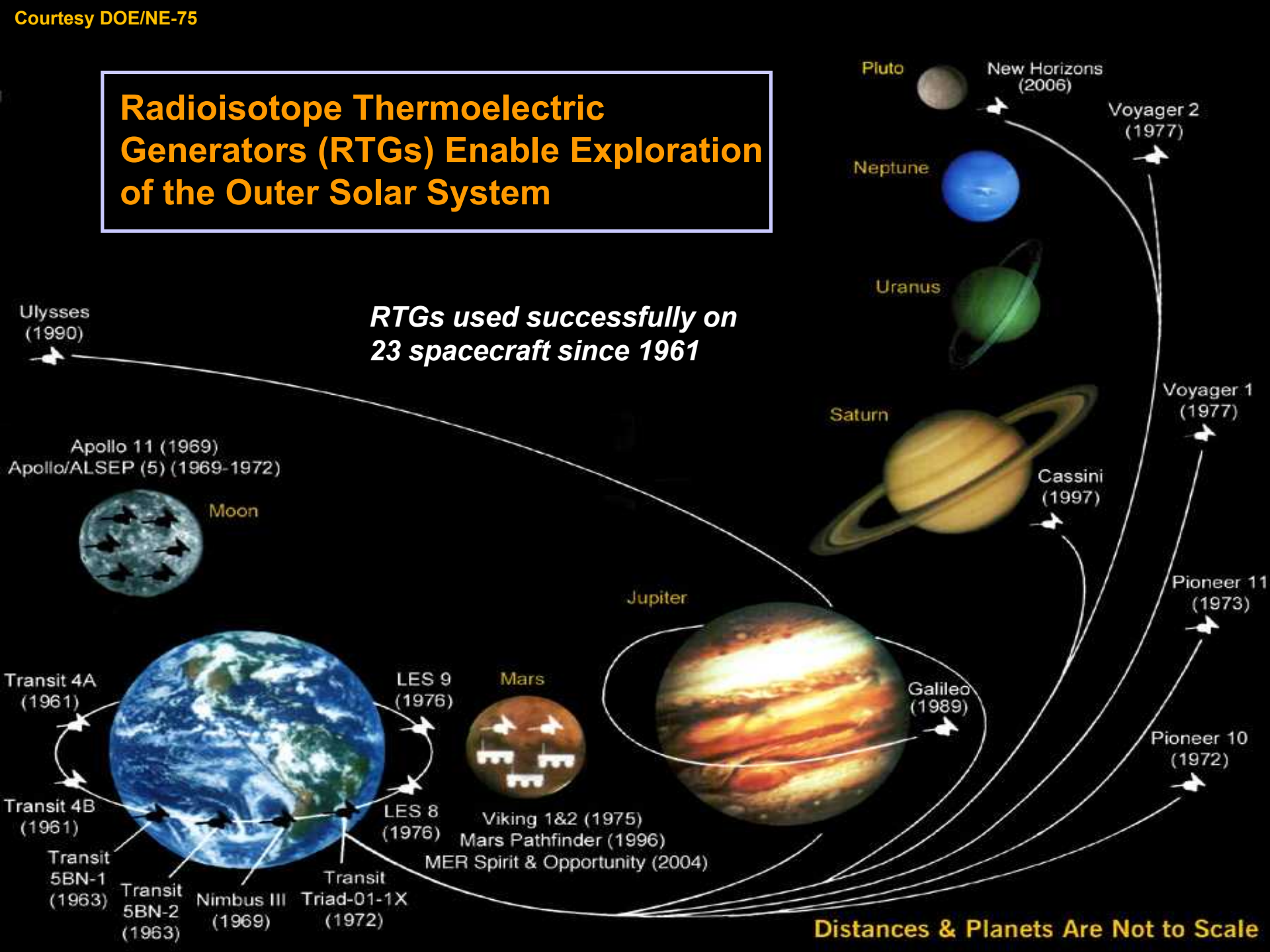
February 27, 2012

Problem: Sunlight is faint beyond Mars, Martian nights are cold



Courtesy DOE/NE-75

Radioisotope Thermoelectric Generators (RTGs) Enable Exploration of the Outer Solar System



Radioisotope Heater Unit

Courtesy DOE/NE-75

Pu-238 oxide (ceramic) inside a platinum-rhodium clad

Graphite insulation and graphite fiber aeroshell

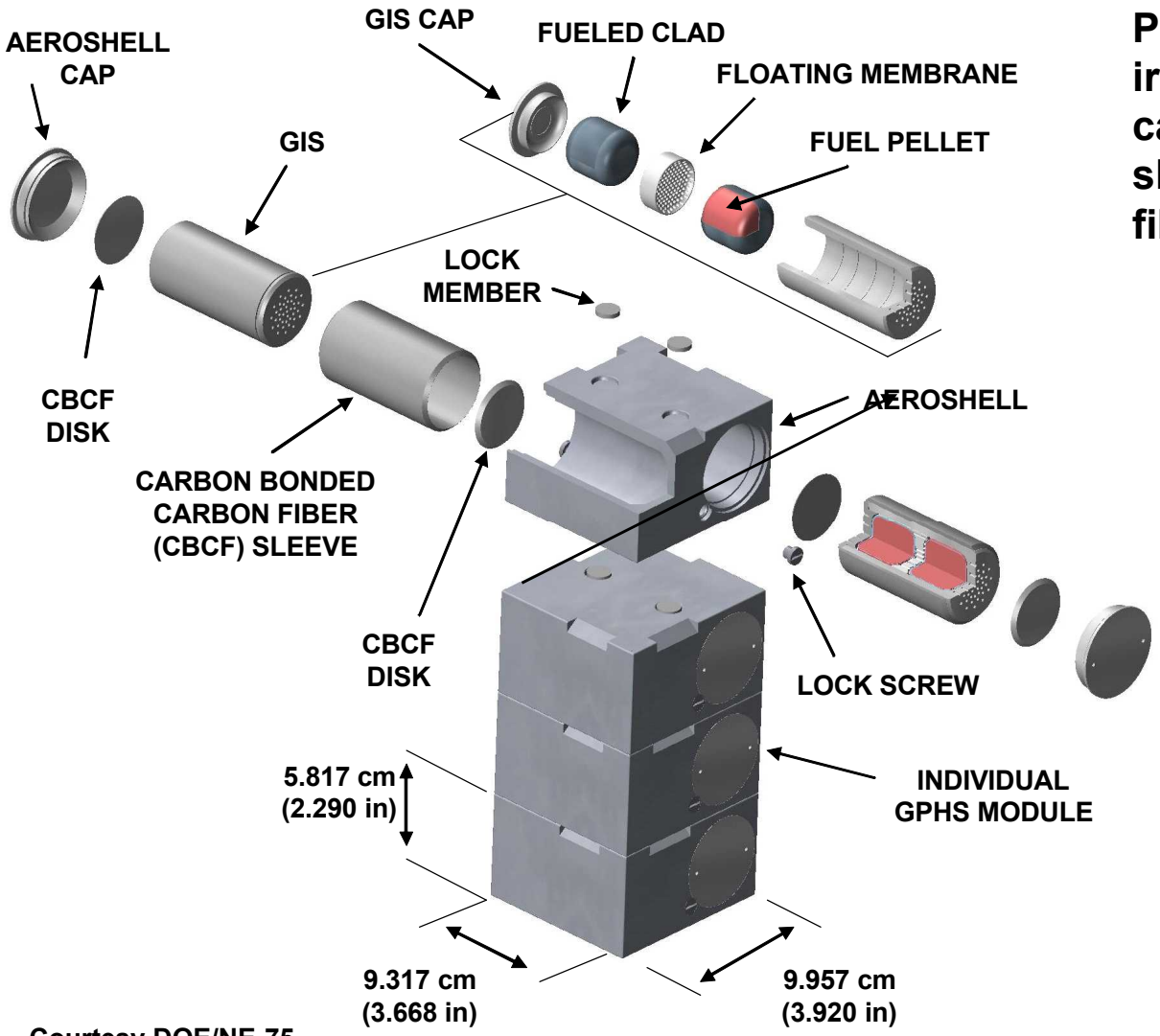
1 Watt of continuous heat from 2.6 g of PuO_2

Plutonium-238 decay provides continuous heat with a half-life of 87.7 years

The alpha-particle radiation can be stopped by a sheet of paper

Small amount of gamma and neutron radiation escapes

General Purpose Heat Source (GPHS) Modules for Generating Electricity



PuO_2 (ceramic) with iridium clad, inside a carbon fiber impact shell, inside a carbon fiber aeroshell

Courtesy DOE/NE-75

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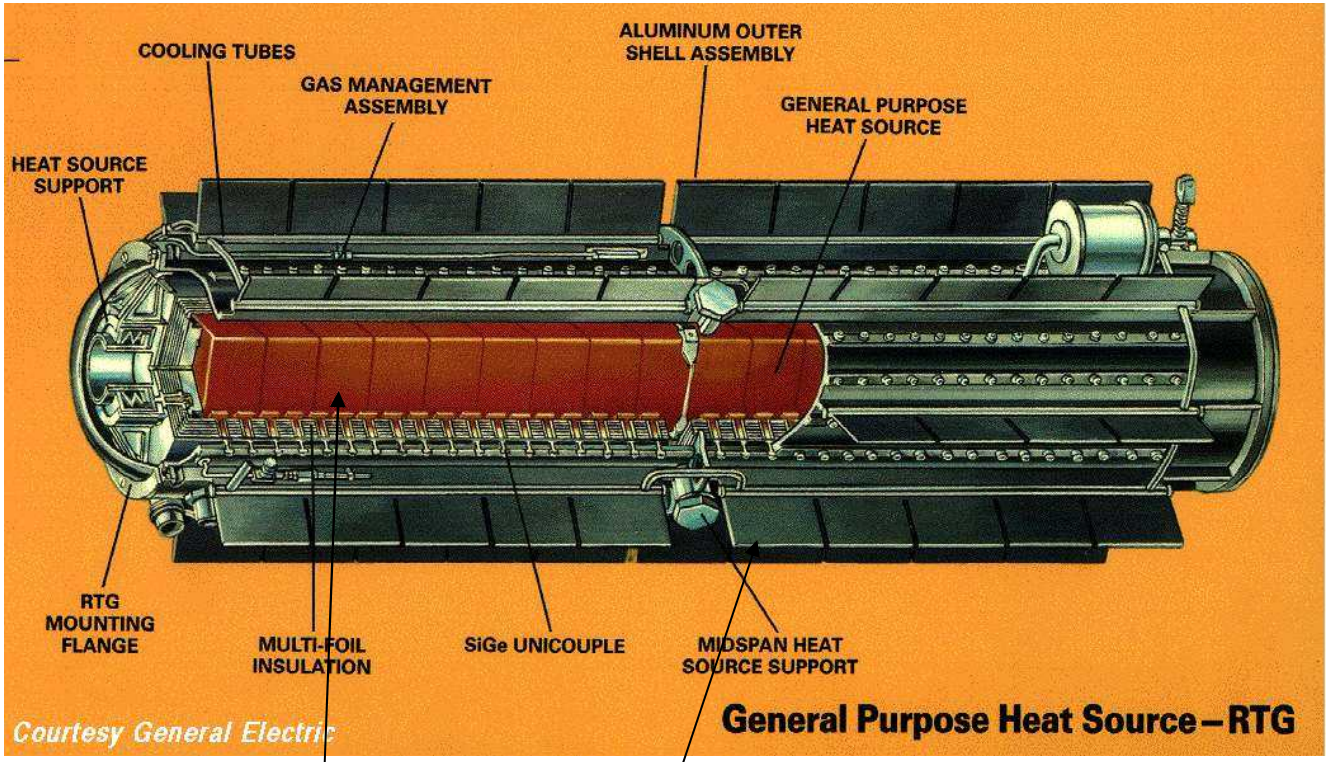
GPHS RTG



Courtesy DOE/NE-75

Pu-238 inside iridium & graphite containers

Thermoelectric power conversion

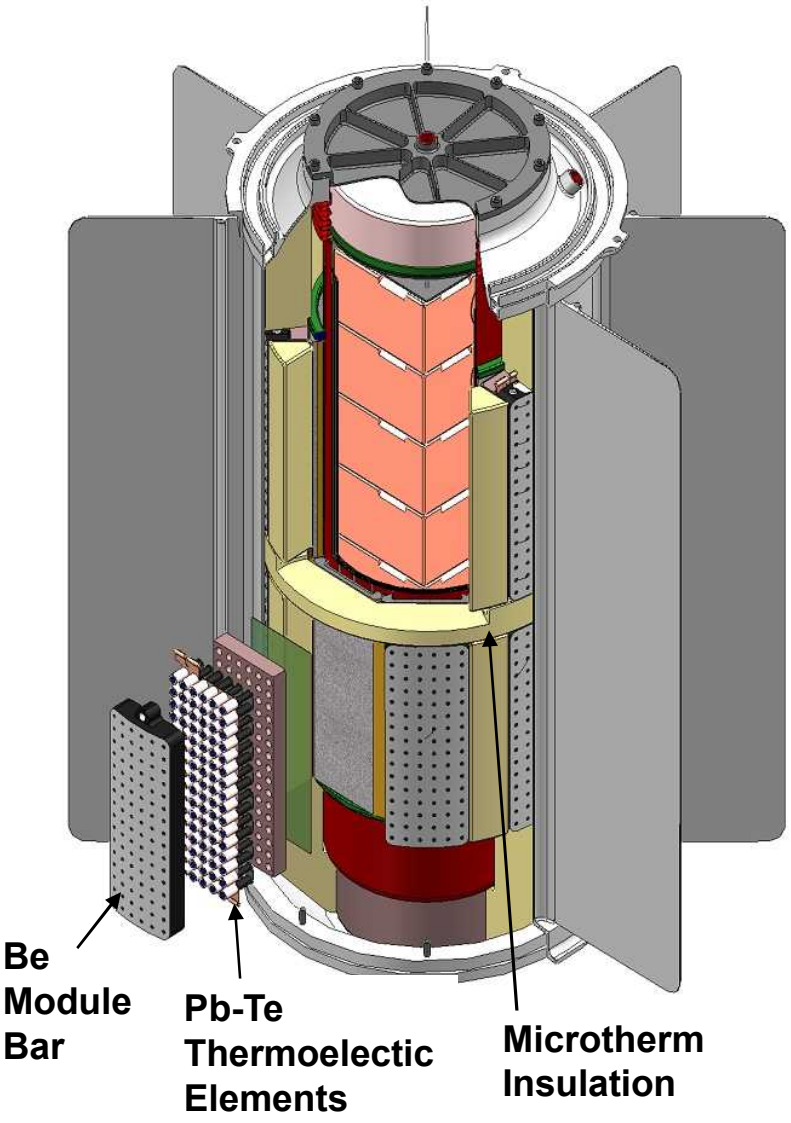
Pu-238 alpha decay
87.8 yr half life

114 cm (45 in)
56 kg (124 lb) total
9.5 kg (21 lb) Pu

0.285 kWe
4.3 kW thermal
6.7% efficient

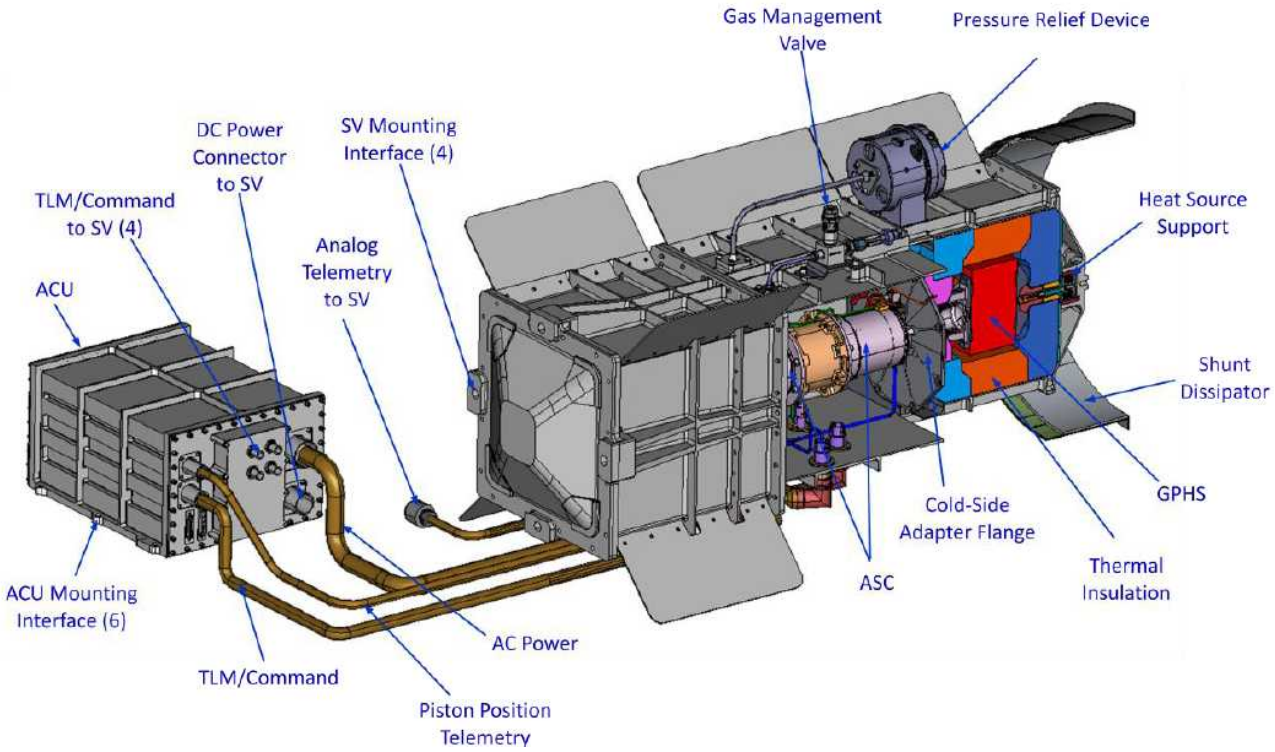
133,000 Curies
Mostly alphas
Some n's & γ's

MMRTG Drawing



Courtesy DOE/NE-75

Advanced Stirling Radioisotope Generator

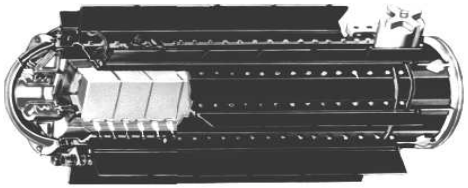


T. Hoye, D. Tantino, J. Chan, Lockheed Marting Space Systems

Proceedings of Nuclear and Emerging Technologies for Space 2011
Albuquerque, NM, February 7-10, 2011
Paper 3620

The Sun: Ulysses

Courtesy NASA

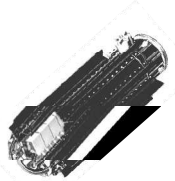


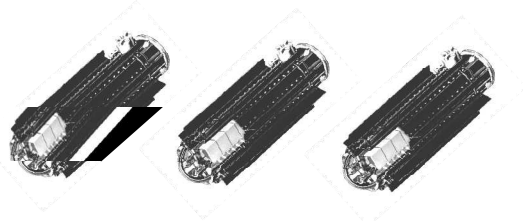
- Ulysses: 1 General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG); 283 watts
- Launched October 1990
  - Operated through 2008—17 years—4x expected mission life

Venus: Galileo & Cassini Flyby's

Galileo, Courtesy NASA

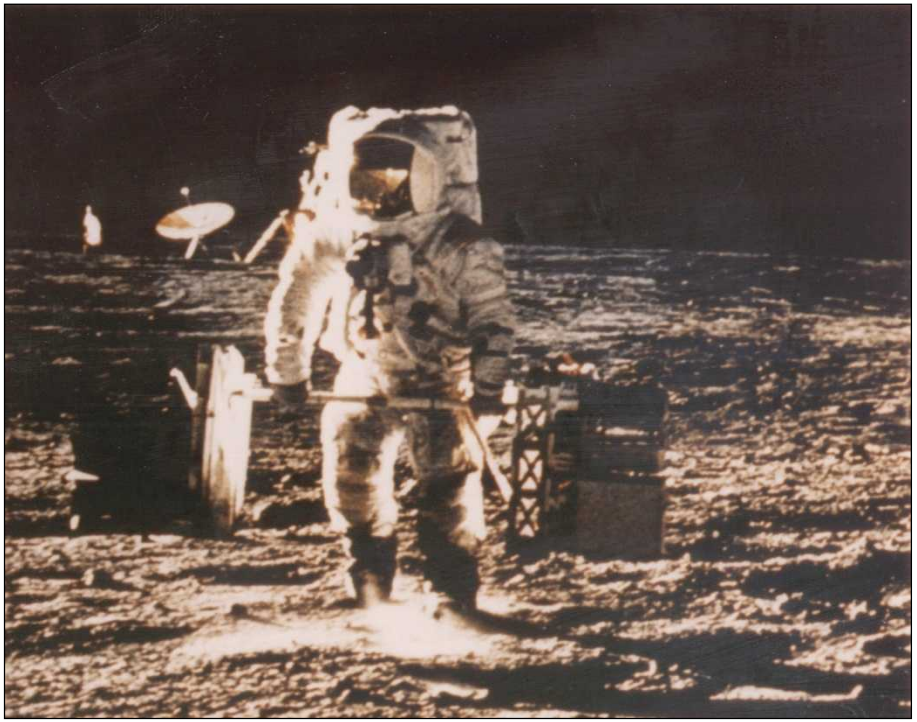
Cassini, Courtesy NASA



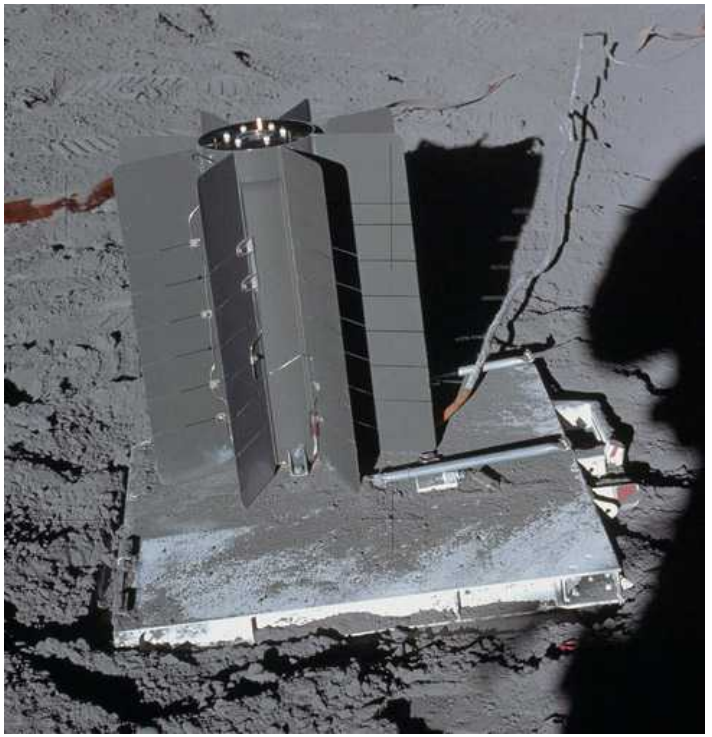


- Visited Galileo and Cassini spacecraft during gravity assist flybys
  - Launches 1989 and 1997
  - Galileo: 2 GPHS-RTGs; 283 watts each
  - Cassini: 3 GPHS-RTGs; 296 watts each

The Moon: Apollo ALSEPs



Courtesy NASA



Courtesy NASA

- **Apollo Lunar Surface Experiments Package (ALSEP)**
  - **Apollo 12, 14, 15, 16, 17: Launched Nov 1969—Dec 1972**
  - **Space Nuclear Auxiliary Power 27 (SNAP-27) RTGs; 72 watts**
  - **Operated Nov 1969 through Sep 1977**
    - **Design life 1 year; provided data 8 years**
    - **Thermal environments: -169° C to 117° C**
    - **Surface and atmospheric data**

Mars—Viking 1 and 2

Viking 2, Courtesy NASA

Viking 2 on Mars Utopian Plain
Courtesy NASA

- Viking 1 (launched 1975); Viking 2 (1975)
- Powered by 2 SNAP-19 RTGs; ~ 42 Watts
- Viking 1 lander operated for 6 years
- Viking 2 lander operated for 3.5 years

Mars Rovers: Radioisotope Heater Units (RHUs)

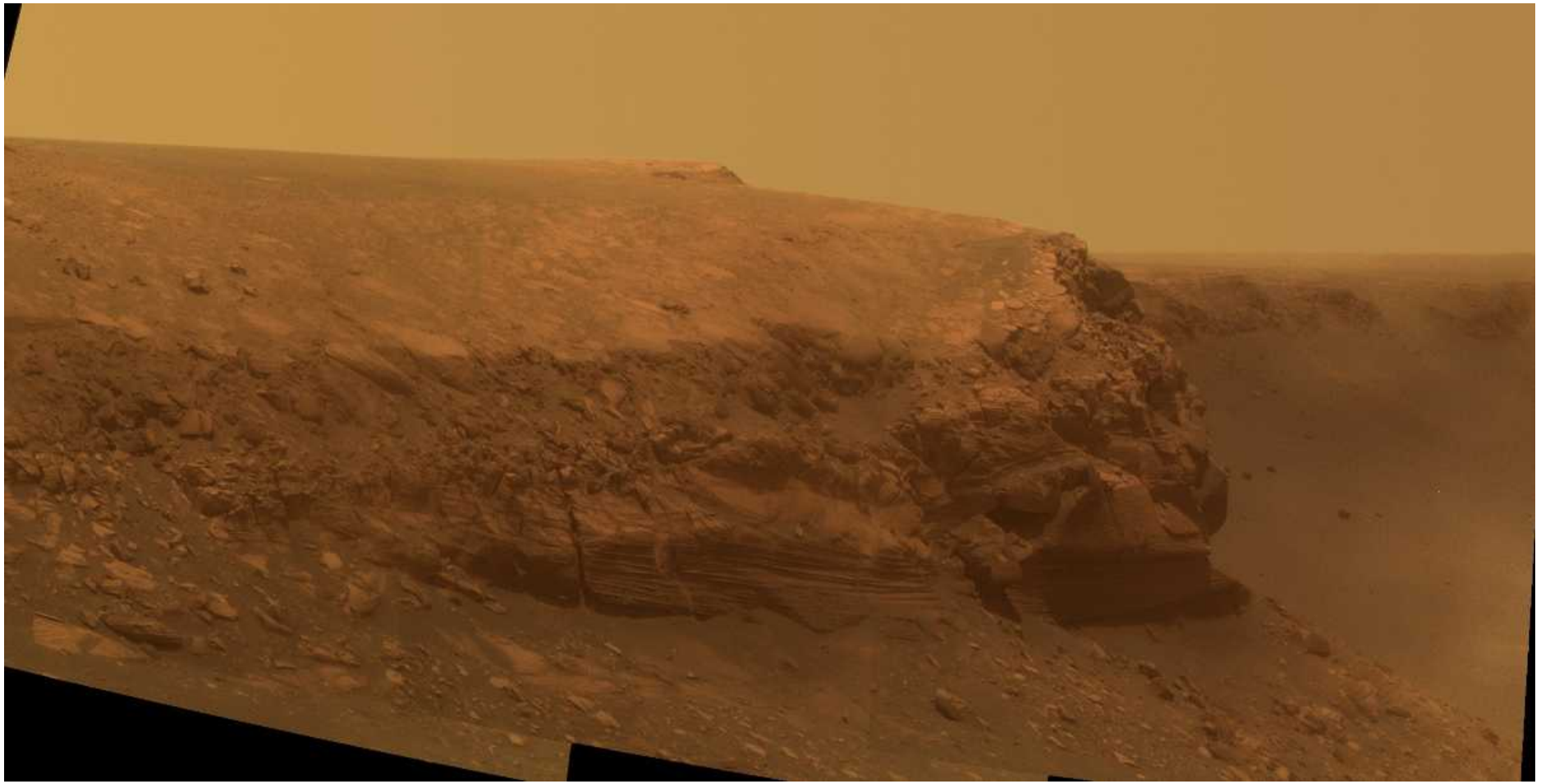
Sojourner Rover, Courtesy NASA

Courtesy DOE/NE-75

MER 20O3 Rover, Courtesy NASA

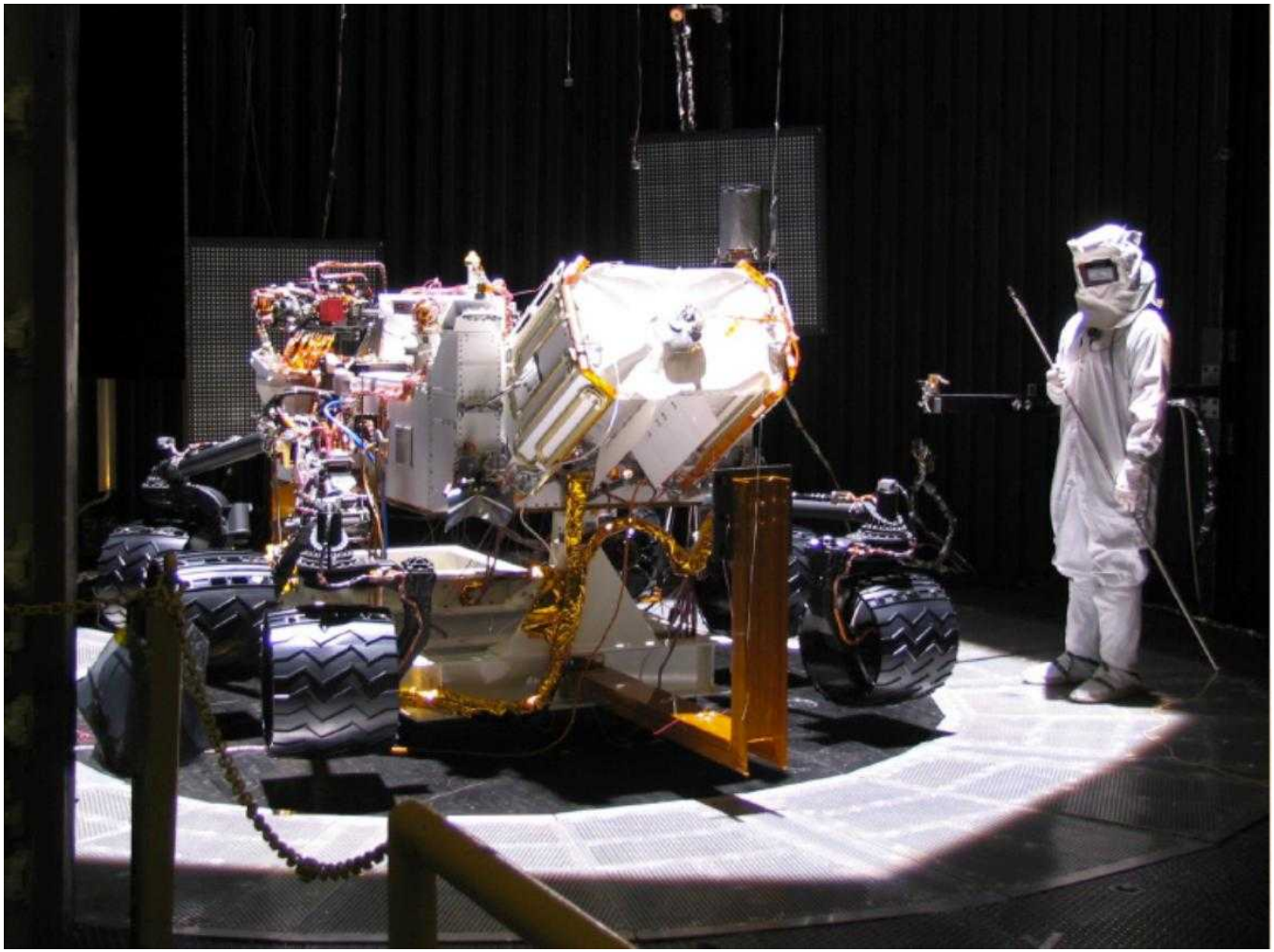
- **Mars Pathfinder-Sojourner Truth Rover (1996); Mars Exploration Rovers-Spirit and Opportunity (2003)**
  - **Mars Pathfinder and MER 2003 Rovers warmed by Radioisotope Heater Units (RHUs)**
  - **Mars Pathfinder operated for 3 months exceeding its design life by a factor of 12**
  - **MER 2003 rovers designed for 90 days operation**

MER Opportunity: Victoria Crater

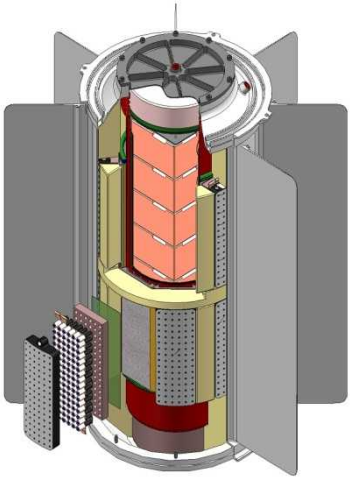


Courtesy NASA/JPL

Mars Science Laboratory (MSL)



- MSL Rover size of a small car
- Launched Nov 26, 2011
- Powered by Multi-Mission RTG; 120 watts
- To operate 1 Martian year (1.8 years)



MMRTG

Courtesy NASA/JPL

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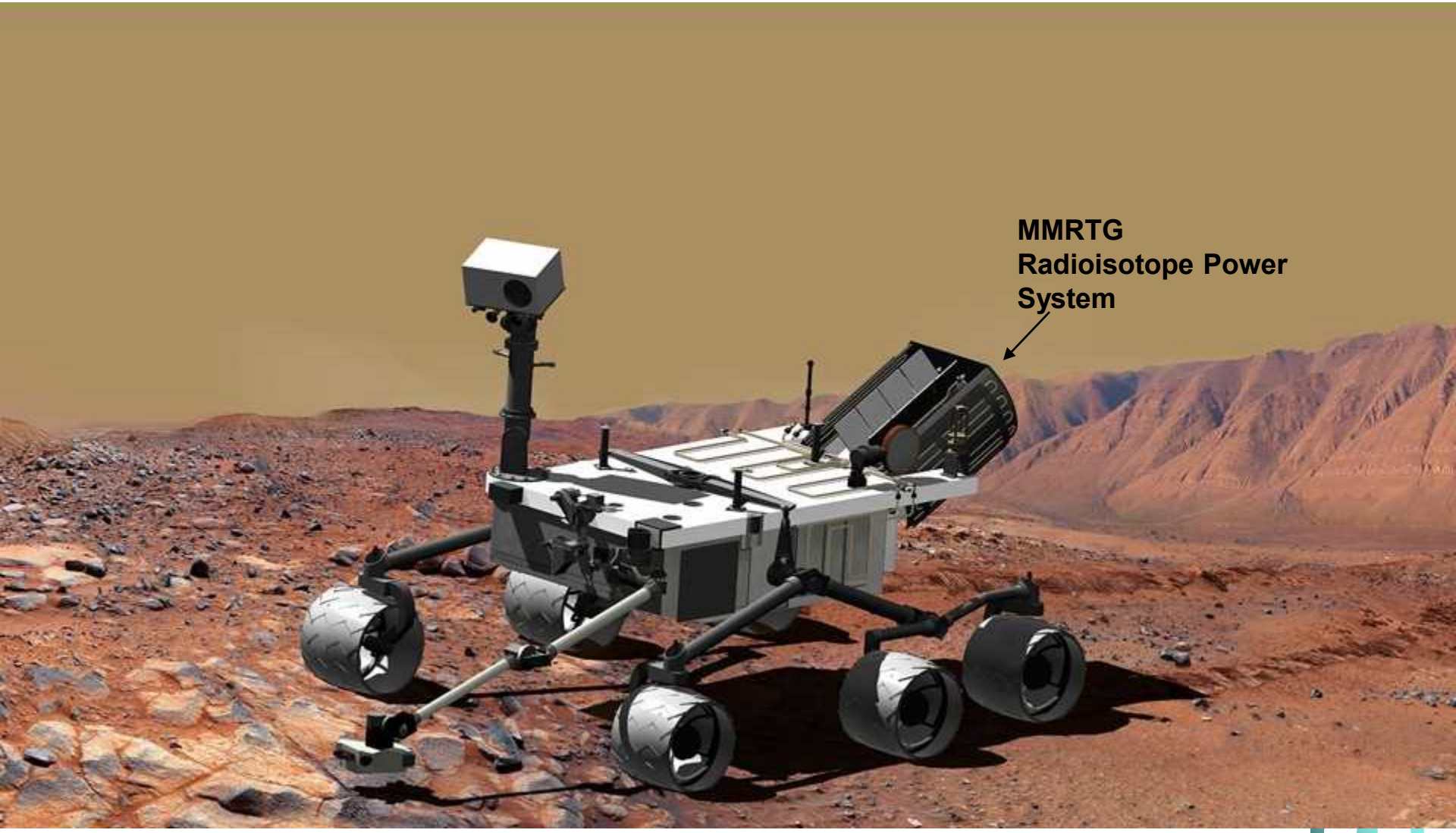
Mars Science Laboratory

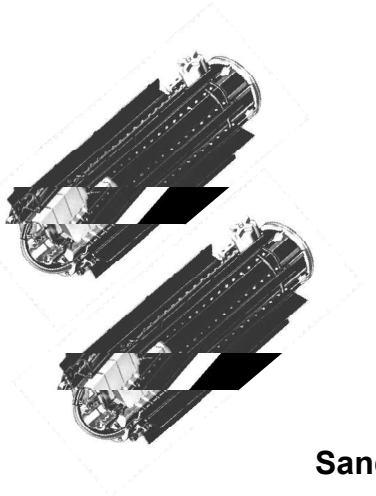


Courtesy NASA/JPL

Jupiter: Pioneer 10, 11, Voyager 1, 2, Galileo

Courtesy NASA/JPL

- Multiplanet probes, Pioneer 10 and 11, Voyager 1 and 2, and Pluto New Horizons performed flybys of Jupiter on their way to edge of the solar system
- Galileo orbiter launch in 1989 arrived at Jupiter in 1995
- Powered by 2 GPHS-RTGs producing ~ 288 watts each
- Primary mission completed December 1997; extended 3 years; ended September 2003 for mission life from launch of 14 years



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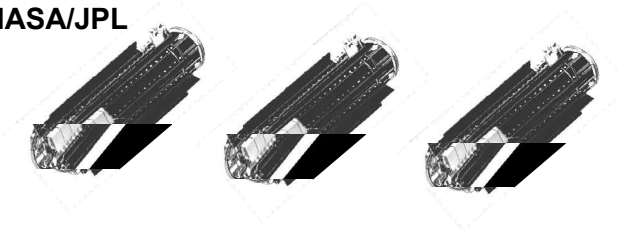
Saturn: Pioneer 10, Voyager 1, 2, Cassini

Courtesy NASA/JPL



- Cassini spacecraft with Huygens probe launch in October 1997, arrived at Saturn June 2004 with its 4-year prime mission ending in July 2008 and extended to September 2010 for a total 13 year life
- Powered by 3 GPHS-RTGs; ~295 watts each
- Selected accomplishments: Huygens probe landed on Titan; during first 4 years orbited Saturn 70 times; collected data about Saturn's rings, flew a water plume from Enceladus
- Pioneer 10, Voyager 1 and 2 also flew by Saturn

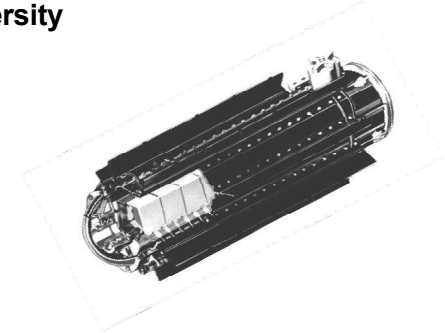
Uranus and Neptune: Voyager 2

Courtesy NASA/JPL

- Voyager 2, launched in 1977, flew by Uranus in 1986 and was at its closest approach to Uranus in 1989
  - 3 Multi-Hundred Watt RTGs; 159 watts each

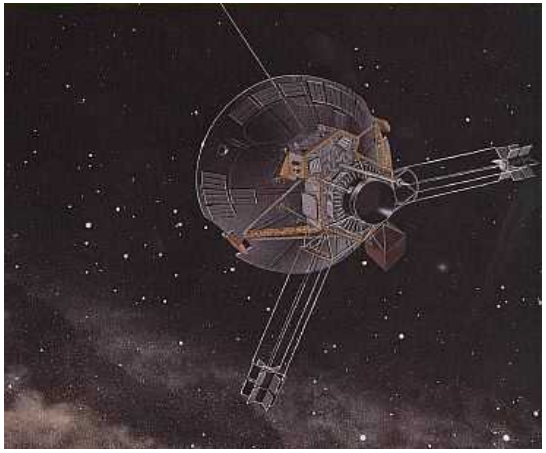
Pluto: Pluto New Horizons

Courtesy Johns Hopkins University
Applied Physics Laboratory



- PNH spacecraft launched January 2006 on its journey to Pluto in July 2015 with a Gravity Assist at Jupiter in February 2007
  - Will continue on to study objects in the Kuiper Belt
  - Powered by 1 GPHS-RTG; 250 watts

Deep Space: Pioneer 10, 11, Voyager 1, 2



Pioneer 10
Courtesy NASA

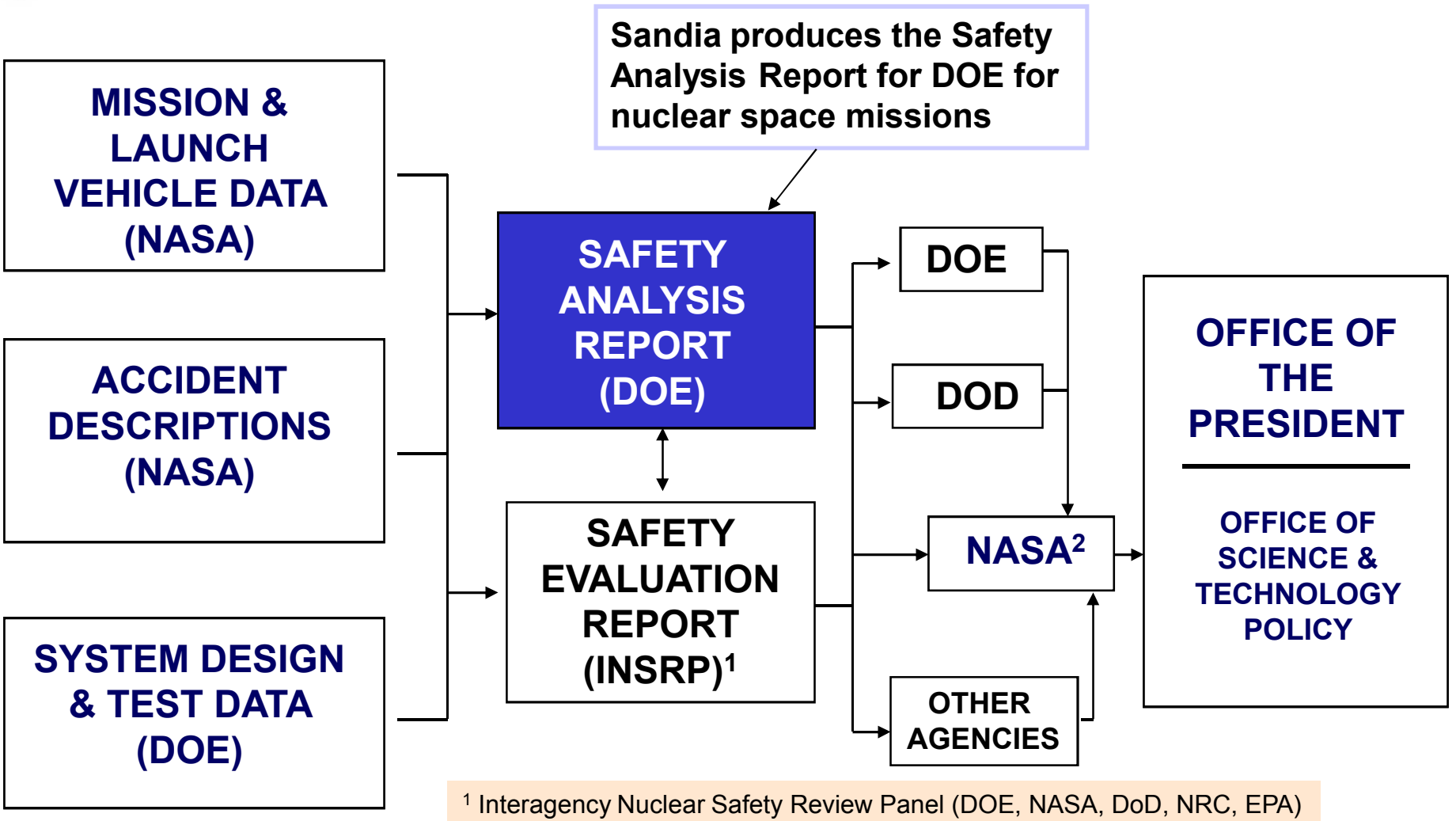
SNAP-19 RTG

Voyager 2 Courtesy NASA/JPL

- Pioneer 10 (1972) and 11 (1973) were each powered by 4 SNAP-19 RTGs; 40 watts each
  - At last contact, Pioneer 10 was 7.6 billion miles from Earth; originally designed for a 21 month mission and operated more than 30 years; mission ended 1997; Pioneer 11 mission ended 1995

- Voyager 1 and 2 (launched 1977)
  - Powered by 3 Multi-Hundred Watt RTGs; ~155-159 watts each
  - Continuing to operate at this time
  - Voyager 1 5.7 billion kilometers from Sun; Voyager 2—12.7 billion kilometers
  - Crossed the heliosphere in December 2004 and August 2007

Presidential Directive / NSC-25 Requires Presidential Approval (or Designee) for All Launches with Nuclear Payload



[1] Interagency Nuclear Safety Review Panel (DOE, NASA, DoD, NRC, EPA)
[2] Responsible mission agency makes launch recommendation

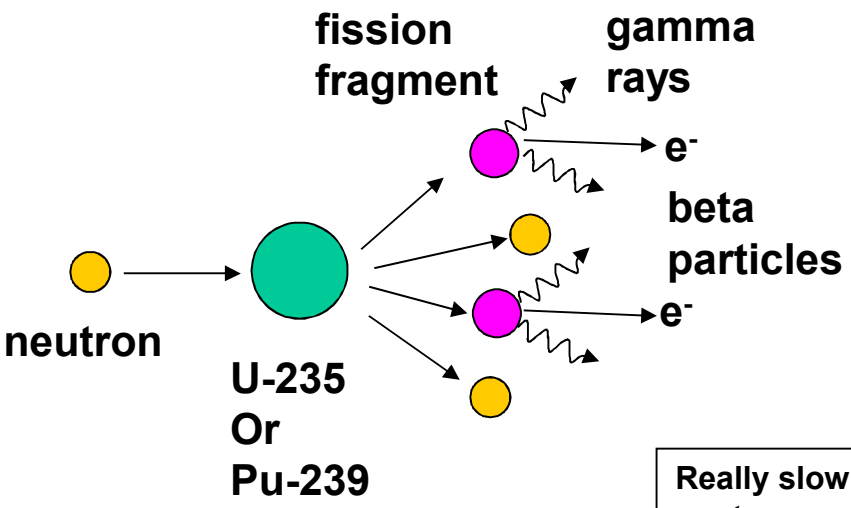
Reactor electric power and propulsion

Courtesy NASA

Courtesy General Atomics

1 kg of U-235 provides 8 times more energy than all the fuel in the shuttle main tank.

Nuclear Reactor Basics



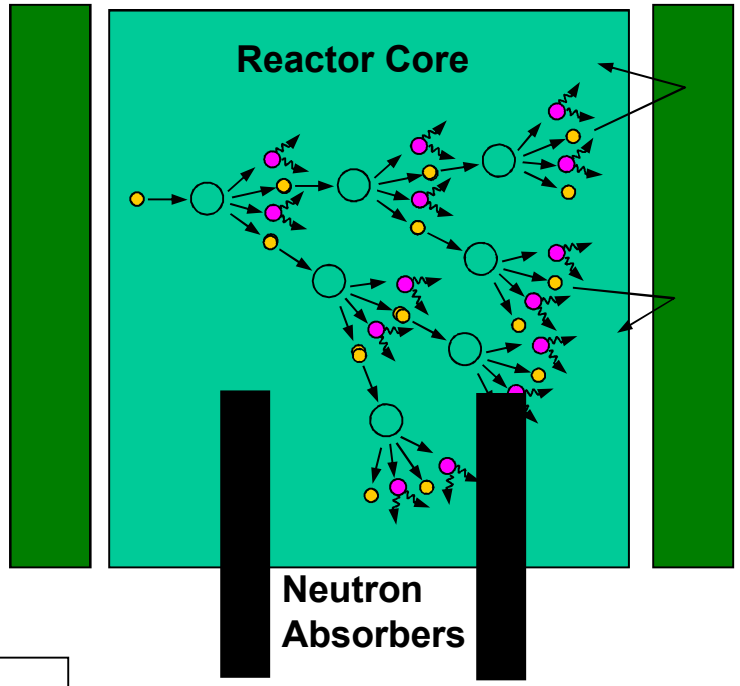
Fission Process

Fission fragments:	165 MeV
Prompt gammas:	7 MeV
Prompt neutrons:	5 MeV
Delayed betas:	7 MeV
Delayed gammas:	6 MeV
Neutrinos:	10 MeV

Really slow neutrons fission better than fast ones

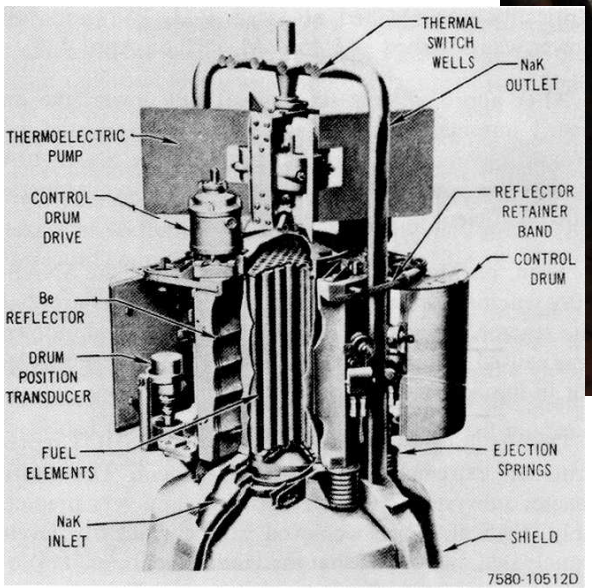
Hot reactors allow more neutron leakage

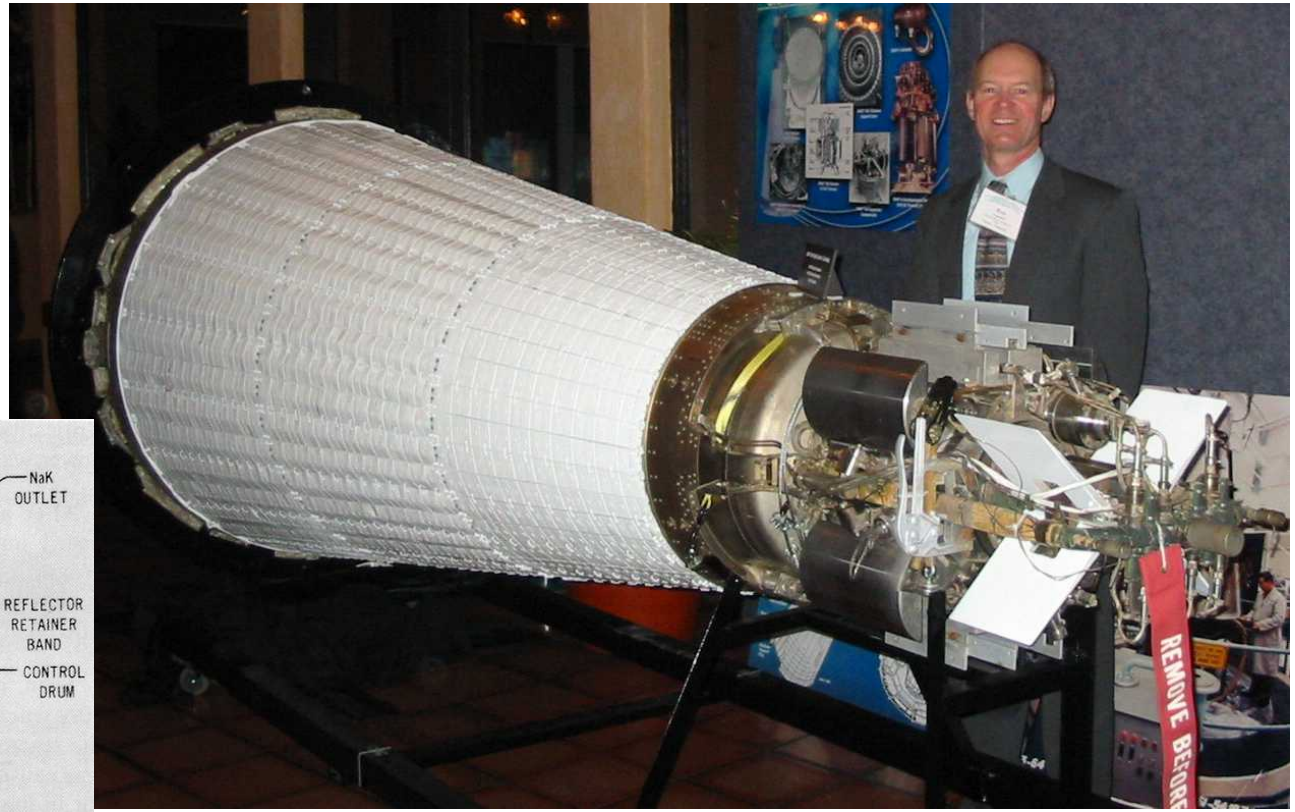
Hot materials absorb more neutrons, sometimes



Reactor core must balance neutron production via fission with neutron absorption and leakage: "Critical chain reaction"

SNAP-10A: Only US space reactor flown (1965)





SNAP-10A flight reactor

Electric power	0.5 kW
Thermal power	40 kW
Core & reflectors	125 kg
Total system	436 kg
Space operation	43 days

UZrH fuel
NaK coolant
TE conversion
830 K max

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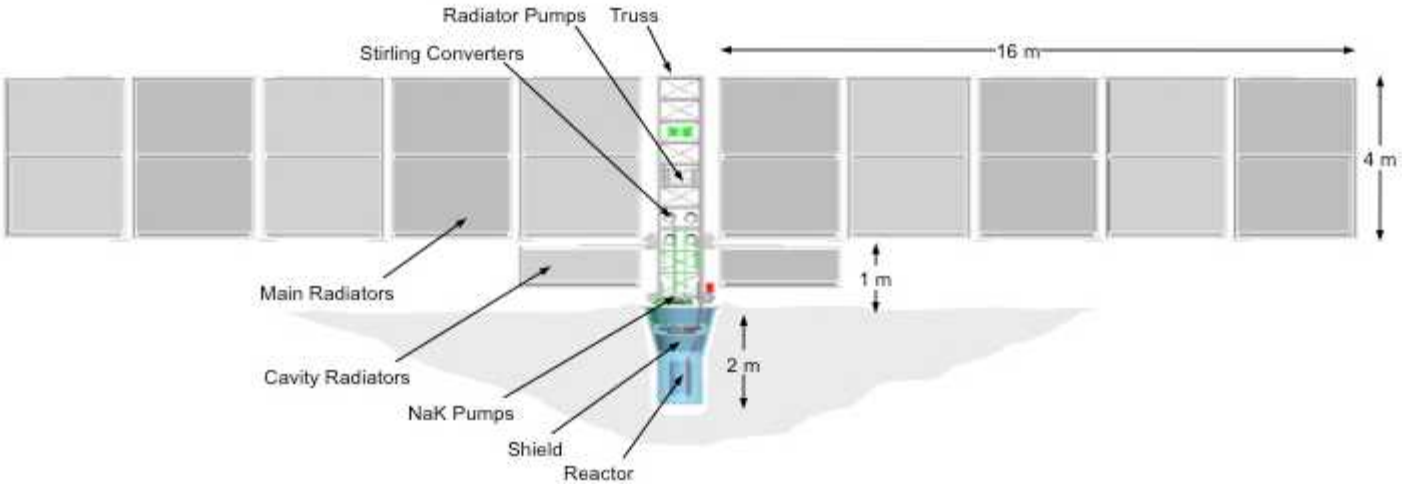
Fission Power System for Lunar Base

- Modular 40 kWe system with 8-year design life suitable for (global) lunar and Mars surface applications
- Emplaced configuration with regolith shielding augmentation permits near-outpost siting (<5 rem/yr at 100 m separation)
- Low temperature, low development risk, liquid-metal (NaK) cooled reactor with UO_2 fuel and stainless steel construction



D. Palac, NASA/GRC

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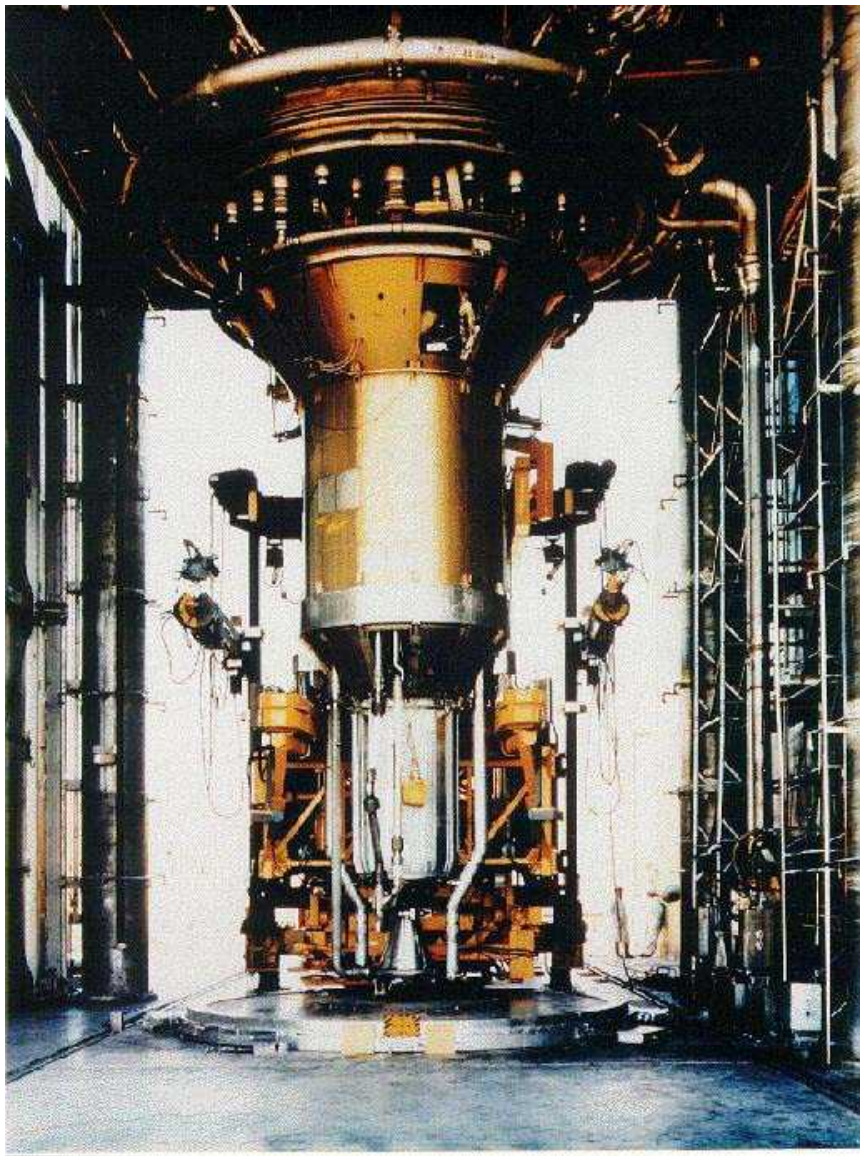
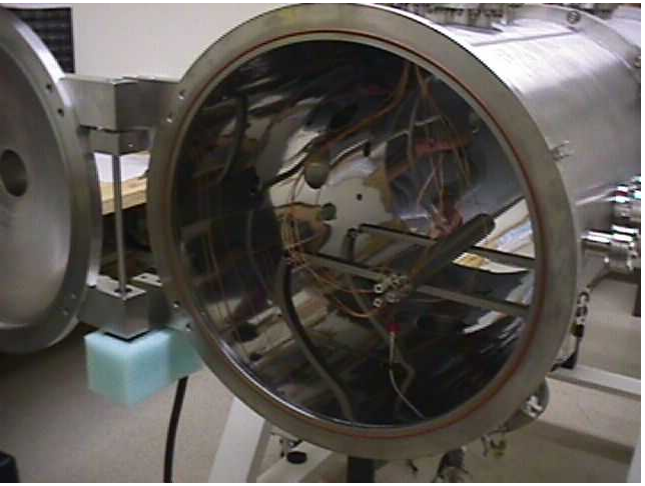
Nuclear Rockets (1965-70)

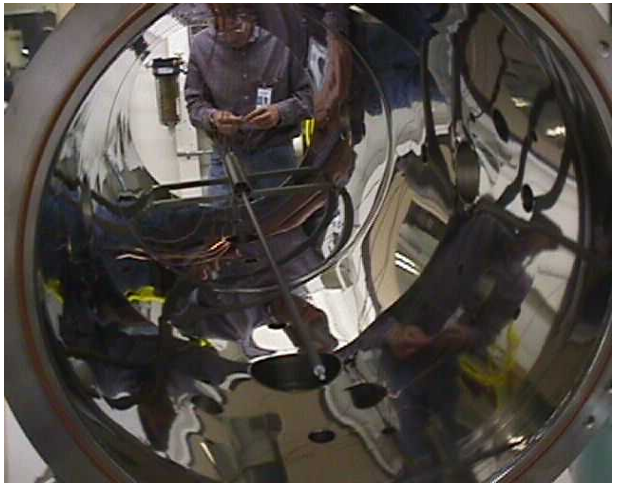


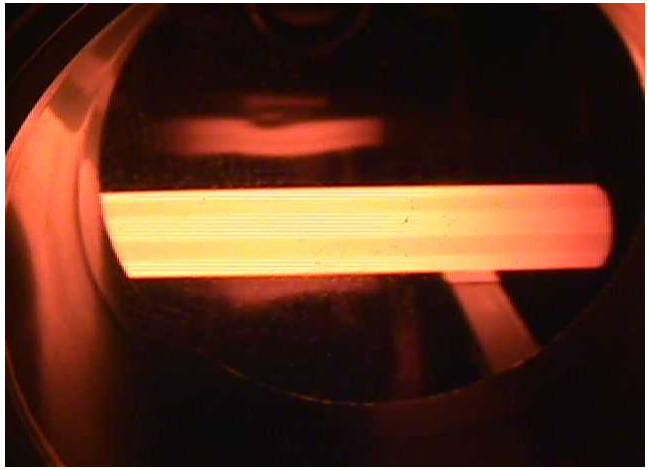
Courtesy NASA

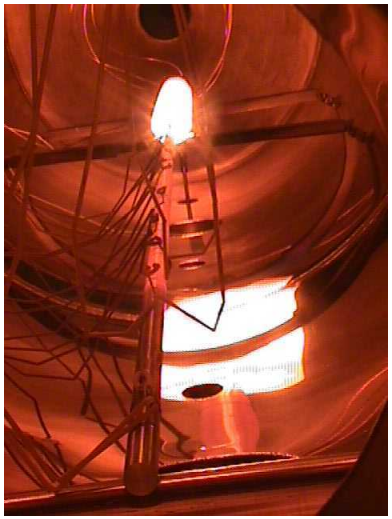
- **Direct thermal propulsion:**
  - **– High T/W Ratio (>> 1)**
  - **– Modest specific impulse (<1000 s)**
  - **– Rover/NERVA program culminated in "Small Engine" design, 875 s Isp, 7300 N thrust, 2550 kg mass.**

Electrically-Heated Hardware Demonstrations Underway









Courtesy NASA

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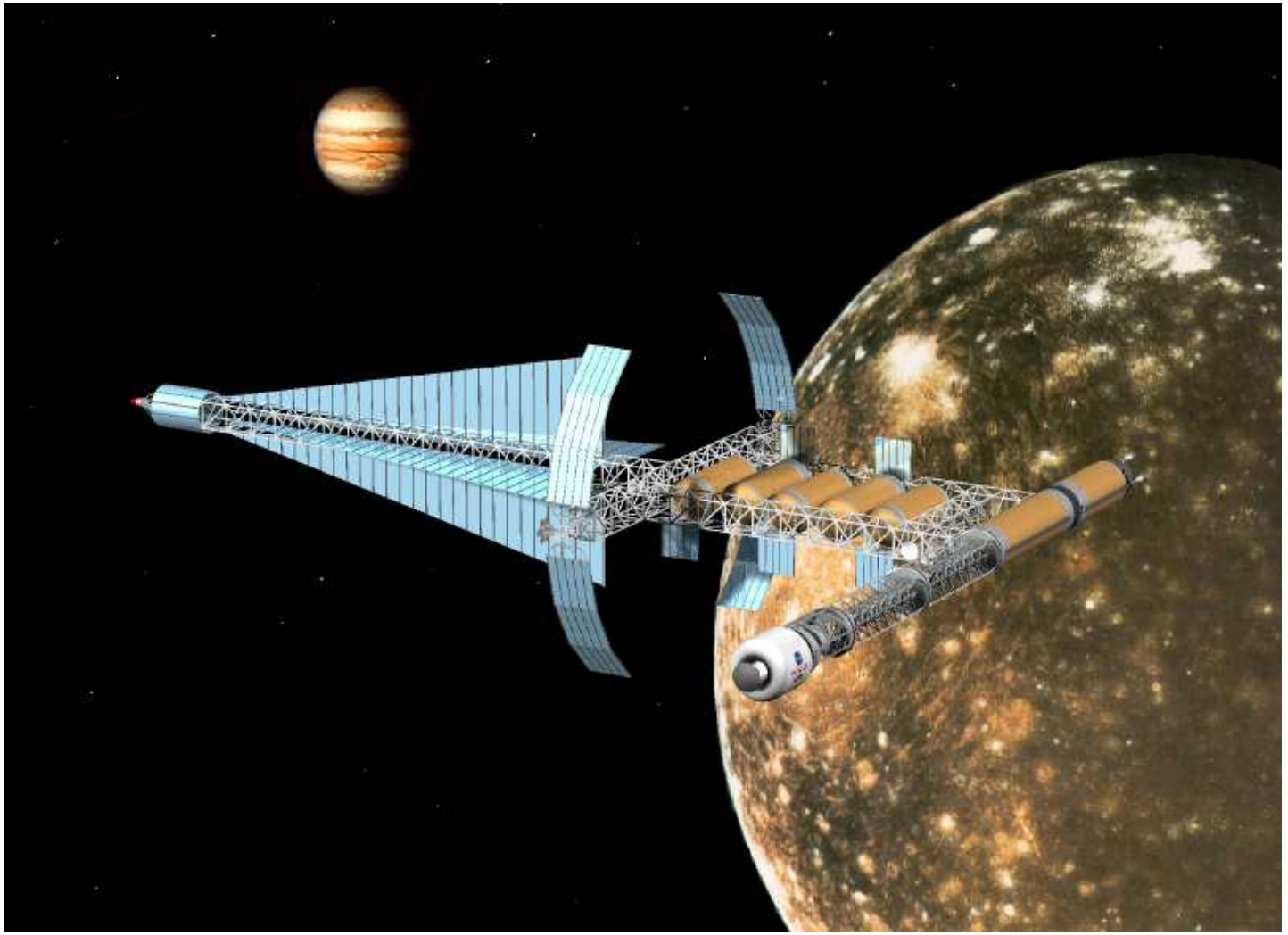
Many System Studies and Visionary Concepts



Nuclear Electric Propulsion Tug & Nuclear Rocket,
Courtesy NASA